PIONEERS IN COLLABORATIVE RESEARCH®

2020 Information Processing Technologies: *A Fundamental Physics Perspective*

Ralph K. Cavin III and Victor V. Zhirnov

Semiconductor Research Corporation

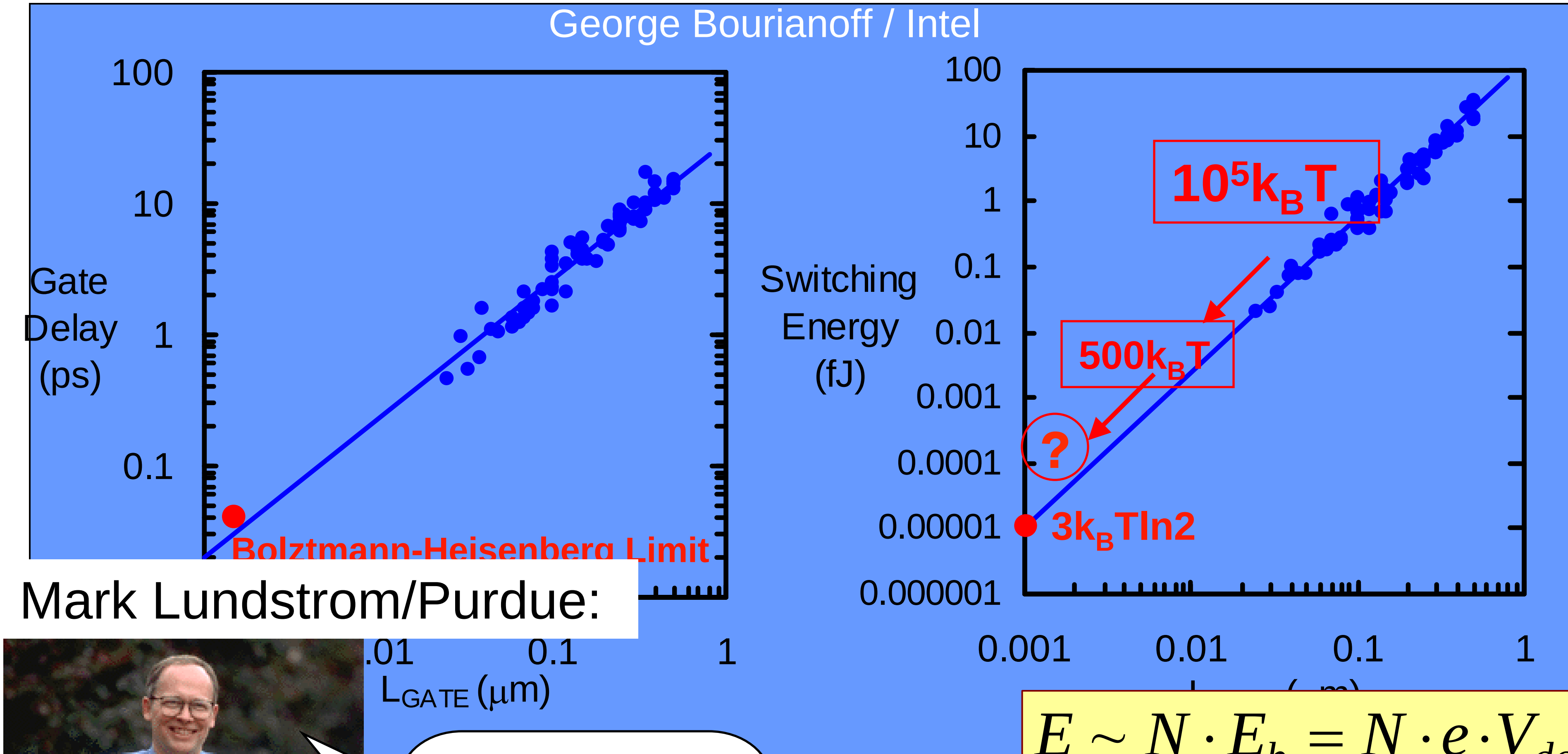
National Science Foundation

Arlington, VA, December 5, 2007

Outline

- Devices
  - What are the fundamental physical limits for binary switches?
  - Could state variables different from charge provide improved performance?
- What can we do about all the heat?
- Are there more effective computing models than von Neumann?
  - Brain?
- Nanofabrication
- Fearless projections for 2020 technology and beyond

CMOS scaling on track to obtain physical limits for electron devices



Mark Lundstrom/Purdue:

Why do we still operate so far above the fundamental limit: Why $10^5\, k_B T \ln 2$ and not $k_B T \ln 2$?

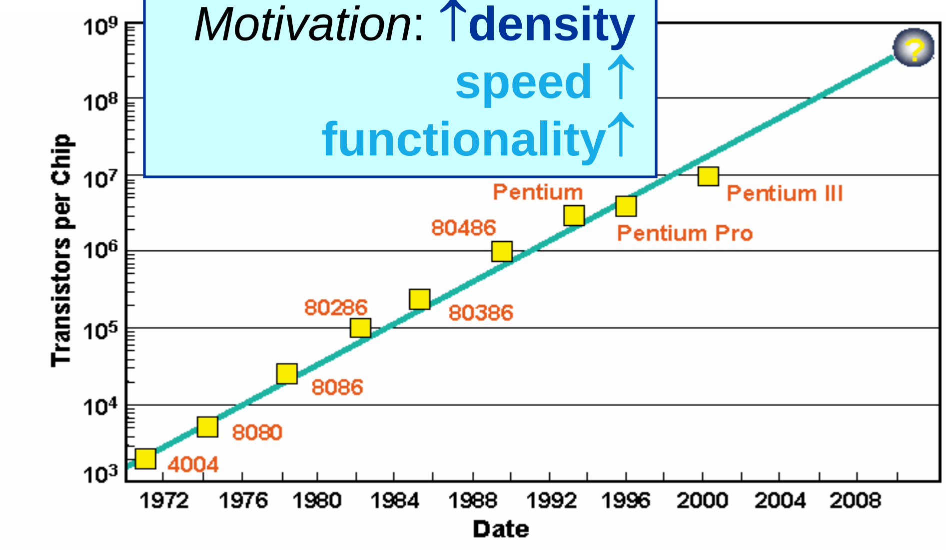
$$E \sim N \cdot E_b = N \cdot e \cdot V_{dd}$$

Answer:

1) **System reliability costs**
2) **Long communication costs**
3) **Fan-Out costs**

Moore’s Law: Transistors per chip

Motivation: ↑**density**
speed ↑
functionality↑



Source: Stan Williams, Hewlett Packard

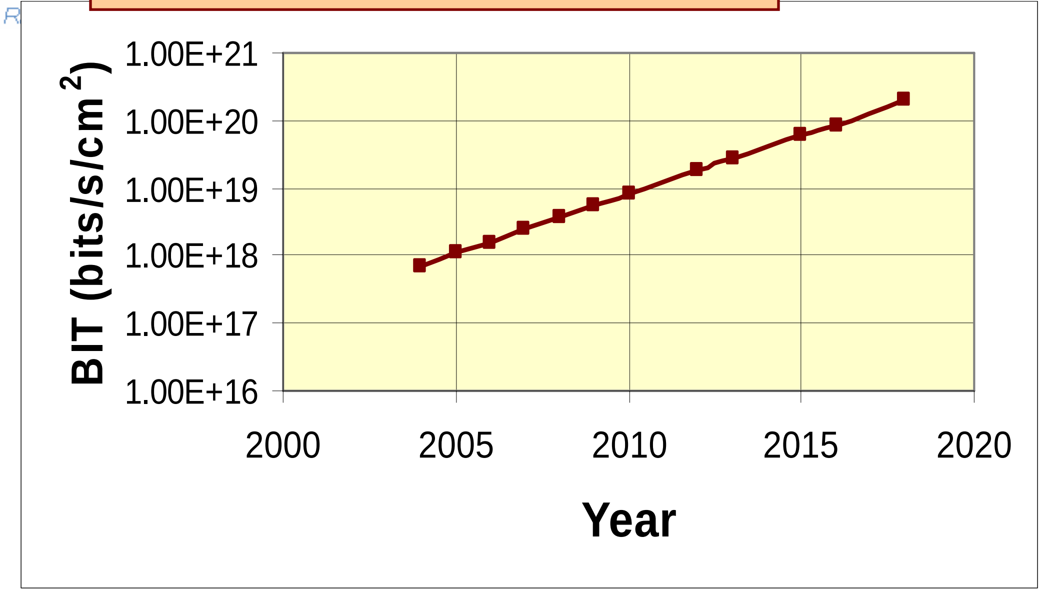
What is the ultimate number of binary transitions per second in a $1cm^2$ chip area?

$$BIT = n_{bit} f$$

- a measure of computational capability on device level

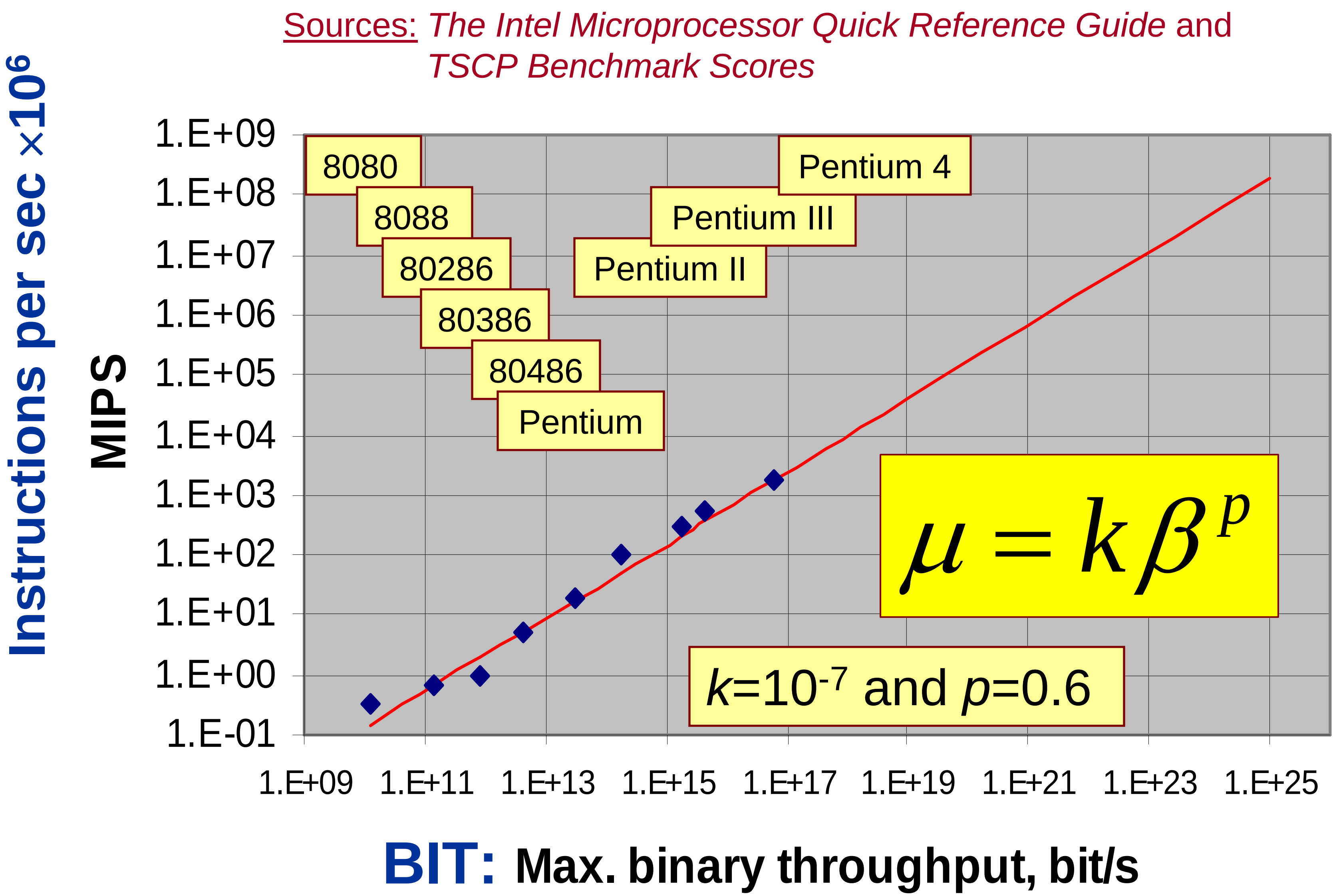
n_{bit} – the number of binary states

f-switching frequency



Why scaling? – To increase the *Binary Information Throughput* (BIT)

Computing Power: MIPS (μ) vs. BIT (β)



We think that all devices operating in an equilibrium with thermal environment are governed by these relations, no matter what state variables are chosen!

$$\Pi_{error} = \exp\left(\frac{E_b}{k_B T}\right)$$

$$\Delta x \Delta p \geq \hbar$$

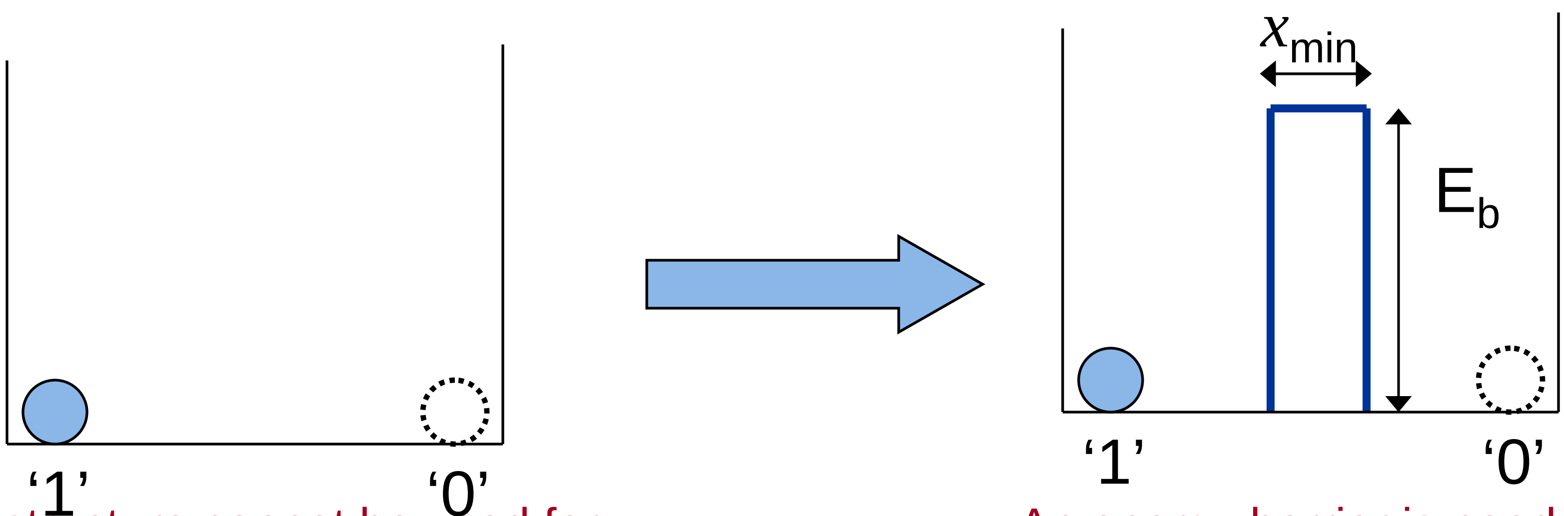
"Boltzman constraint" on minimum switching energy

"Heisenberg constraint" on minimum device size

Nanoscale Devices

$$E_b^{\min} = k_B T \ln 2$$

$$x_{\min} = \frac{\hbar}{\sqrt{2mkT \ln 2}}$$



This structure cannot be used for representation/processing information

An energy barrier is needed to preserve a binary state

Summarizing, what we have learned so far from fundamental physics

1) Minimum energy per binary transition → Boltzmann

$$E_{bit}^{min} = k_B T \ln 2$$

2) Minimum distance between two distinguishable states

$$\Delta x \Delta p \geq \hbar$$

→ Heisenberg

$$x_{min} = a = \frac{\hbar}{\sqrt{2mkT \ln 2}} = 1.5nm(300K)$$

(electronic switch)

3) Minimum state switching time

$$\Delta E \Delta t \geq \hbar$$

→ Heisenberg

$$t_{st} = \frac{\hbar}{kT \ln 2} = 4 \times 10^{-14} s(300K)$$

Total Power Dissipation (@Ebit= $kT\ln(2)$**)**

\- **A Catastrophe!**

$$\boxed{P_{chip} = 4.74 \times 10^6 \frac{W}{cm^2}}$$

Elementary model of heat transfer - Zero–*T* Heisenberg limit

The rate of energy transfer from an atom to a heat transfer agent (e.g. another atom, electron, photon):

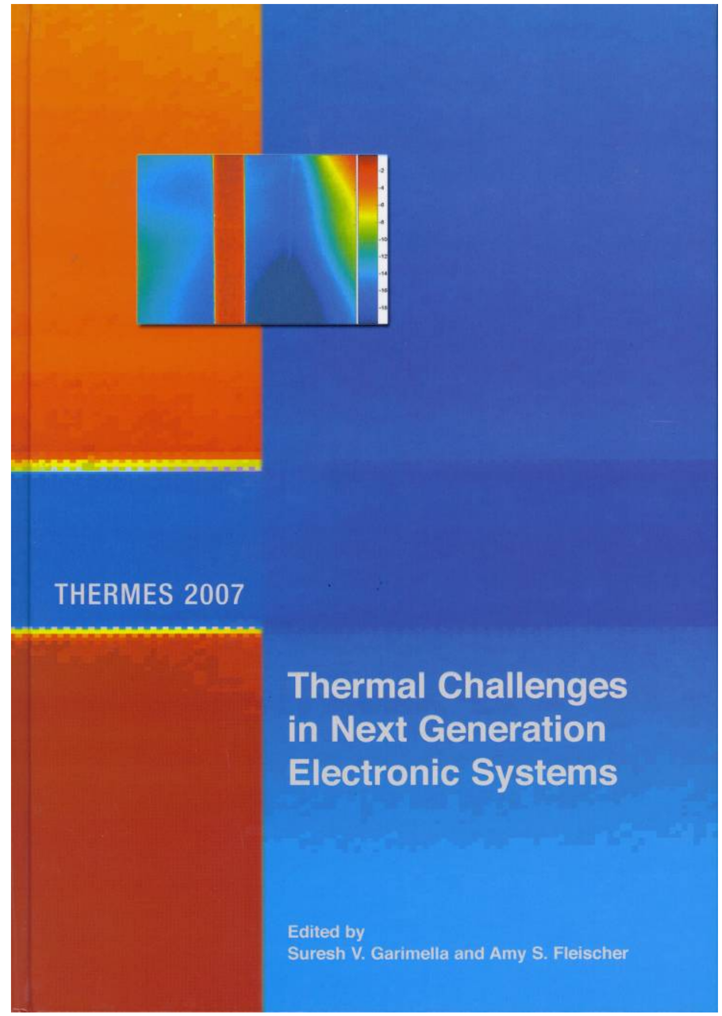
$$\dot{Q} = \frac{\Delta E}{\Delta t}$$

$$\Delta E_{\max} \sim k_B T$$

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

$$\dot{Q}_{\max} = \frac{\Delta E_{\max}}{\Delta t_{\min}} = \frac{2(k_B T)^2}{\hbar}$$

The maximum amount of heat transfer in a system of two heat carriers, e.g. atom-atom, atom-electron, atom-photon



Limits of Cooling?

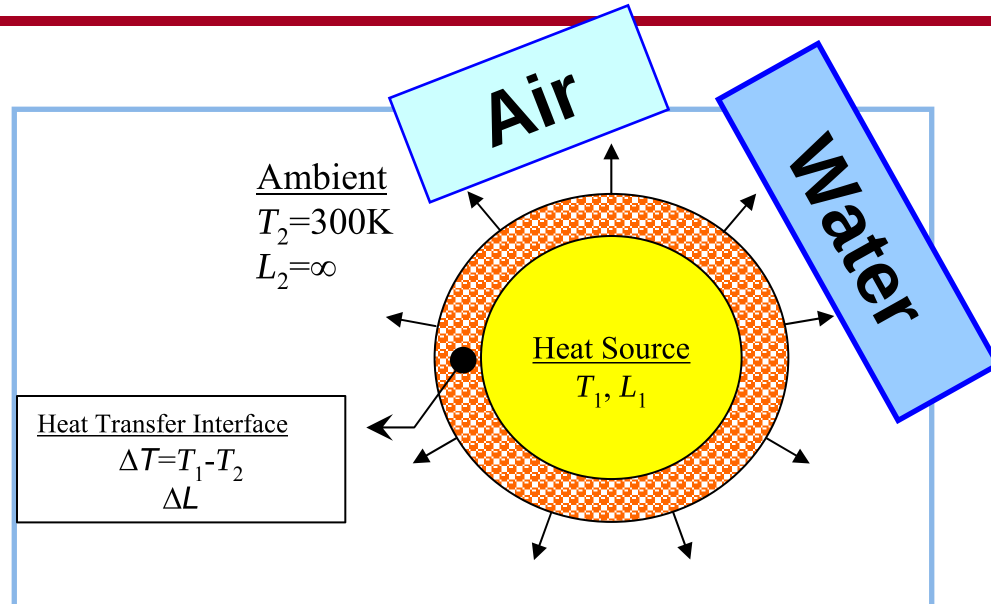
Heisenberg-Boltzmann constant

$$\dot{q}_{\max} = \frac{2(k_B T)^2}{\hbar} \cdot n_s$$

Number of channels

Not enough

Air: $n_s \sim 10^{13}$ cm^{-2}



Boundary parameters for cooling problem

Air

$$64\,\frac{W}{cm^2}$$

Practical limit imposed in 2005 ITRS

Best demonstrated

Water

$$700\,\frac{W}{cm^2}$$

Limits of Heat Transfer to Ambient

Solid-Air

Solid-Water

Heisenberg-Boltzmann Limit

Coherent heat transfer

$$\dot{q}_{max} = 650 \frac{W}{cm^2}$$

$$\dot{q}_{max} = 3.5 \times 10^6 \frac{W}{cm^2}$$

Limits of forced liquid/air cooling

$$\dot{q}_{air} = 172 \frac{W}{cm^2}$$

$$\dot{q}_{water} = 2.6 \times 10^5 \frac{W}{cm^2}$$

Demonstrated

$$\dot{q}_{exp} = 64 \frac{W}{cm^2}$$

$$\dot{q}_{exp} = 700 \frac{W}{cm^2}$$

Gap

$$\frac{q_{max}}{q_{exp}} \approx 10$$

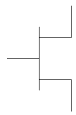
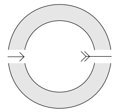
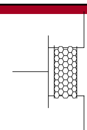
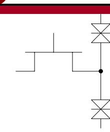
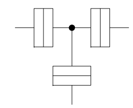
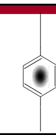
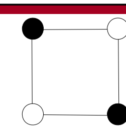
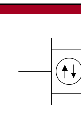
$$\frac{q_{max}}{q_{exp}} \approx 5000$$

We are done with air

More can be done with water

Emerging Research Logic Devices

2003 International Technology Roadmap for Semiconductors

Device								
	FET	*RSFQ*	*1D structures*	*Resonant Tunneling Devices*	*SET*	*Molecular*	*QCA*	*Spin transistor*
Cell Size	100 nm	0.3 µm	100 nm	100 nm	40 nm	Not known	60 nm	100 nm
Density (cm^{-2})	3E9	1E6	3E9	3E9	6E10	1E12	3E10	3E9
Switch Speed	700 GHz	1.2 THz	Not known	1 THz	1 GHz	Not known	30 MHz	700 GHz
Circuit Speed	30 GHz	250–800 GHz	30 GHz	30 GHz	1 GHz	<1 MHz	1 MHz	30 GHz
Switching Energy, J	2×10^{-18}	$>1.4\times10^{-17}$	2×10^{-18}	$>2\times10^{-18}$	$>1.5\times10^{-17}$	1.3×10^{-16}	$>1\times10^{-18}$	2×10^{-18}
Binary Throughput, $GBit/ns/cm^2$	86	0.4	86	86	10	N/A	0.06	86

We HAVE IDENTIFIED NO VIABLE EMERGING LOGIC TECHNOLOGIES for Information Processing beyond CMOS

New Logic Device Concepts are Needed!

ITRS ERD assessment:

we HAVE NO VIABLE EMERGING LOGIC TECHNOLOGIES for Information Processing beyond CMOS.

NRI is looking for new radical solutions

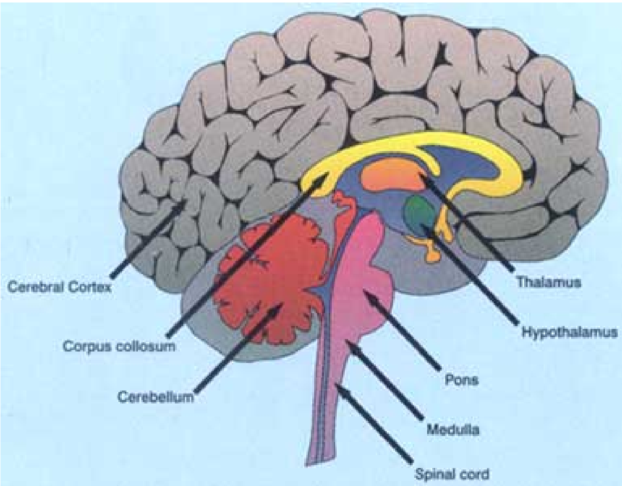
Alternative State Variables: What If We use Spin instead of Charge?

WHY? **For fundamental reasons, CMOS appears to be the preferred solution for electron-based logic**

- **Density**
- **Speed**
- **Energy**

Can we dramatically improve information processing power by utilizing new computational models?

Most complex information-management system in the universe…



	Dell 8250 (Pentium® 4)	Brain
Mass	~25 kg	1.4 kg
Volume	34200 cm^3	1350 cm^3
MIPS	~10^3 MIPS	10^8 MIPS
BIT	<10^{16} bit/s	10^{19}bit/s
Power	**200 W**	**30 W (max)**
	~ 5 MIPS / W	**$3x10^6$ MIPS / W**
	$5x10^6$ k_BT / bit	**700 k_BT/bit**

A CMOS machine at the limits of scaling would use prodigious amounts of power

When will computer hardware match the human brain?

Dell 8250 (Pentium®4)

10^3 MIPS

200 W

x 10^5

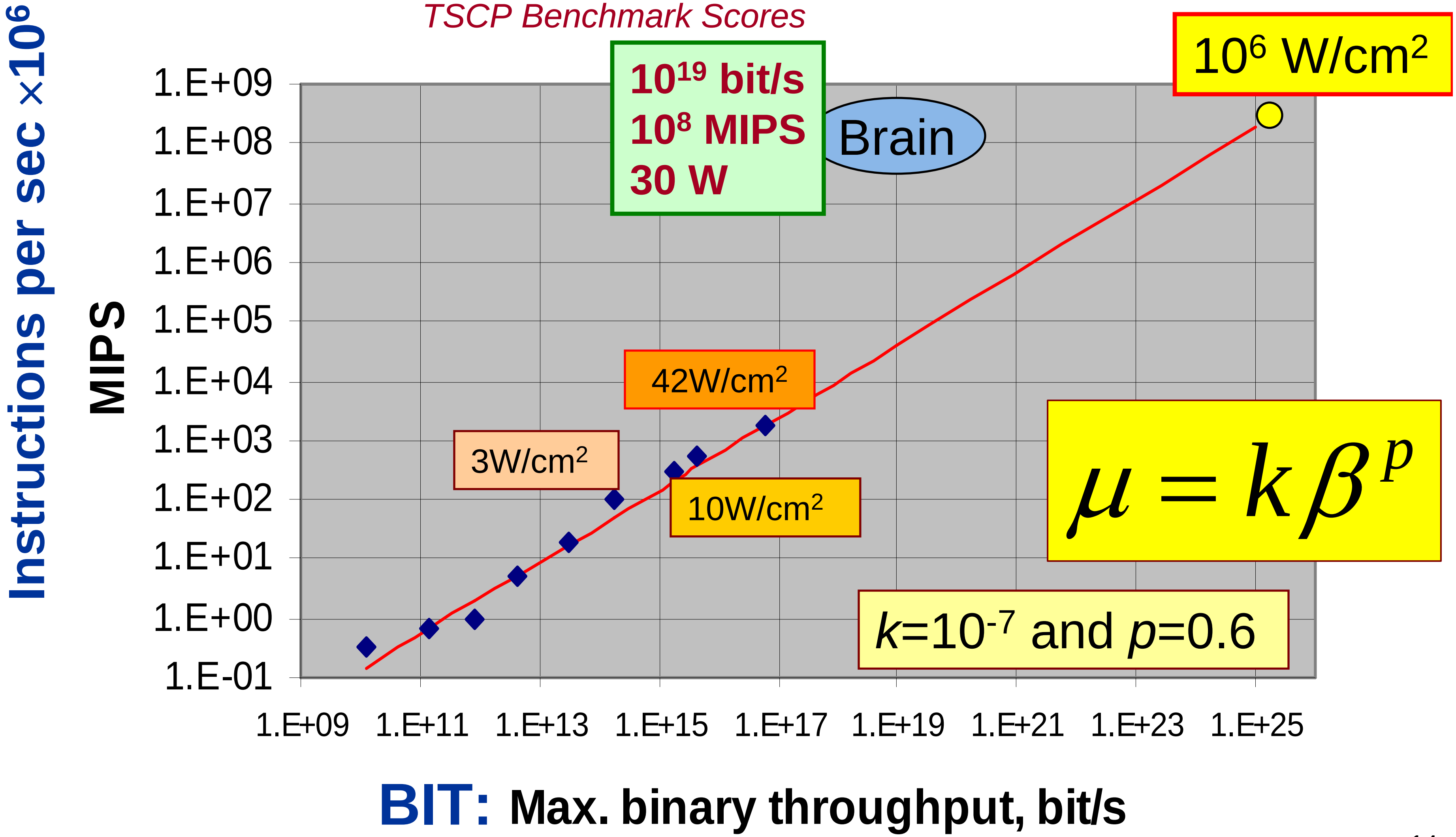
x 10^5

10^8 MIPS

=20,000 000 W

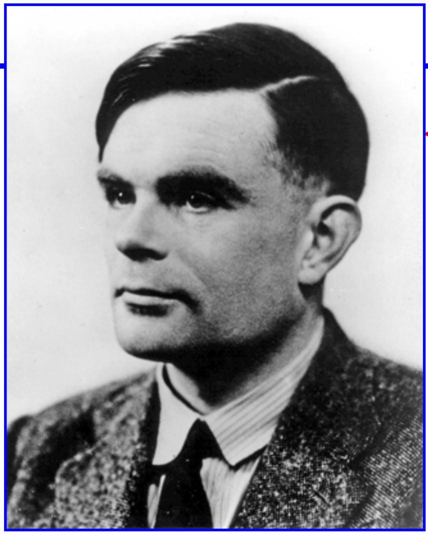
Computing Power: MIPS (μ) vs. BIT (β)

Sources: *The Intel Microprocessor Quick Reference Guide* and *TSCP Benchmark Scores*



Turing-Heisenberg Rapprochement?

Instructions per second
a measure of computational capability on the processor level



Alan Turing

$$\mu = k\beta^{p}$$

Binary Information Throughput
a measure of computational capability on device level

Werner Heisenberg

Ludwig Boltzmann

Observations on Biological Computation

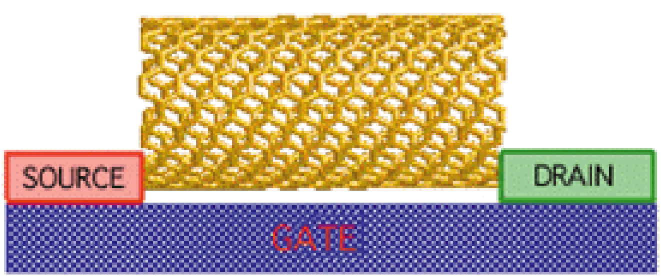
- Biological systems achieve extraordinary performance for cognitive applications with relatively low energy utilization
  - Does the brain operate at the threshold of error creation to obtain low energy utilization?
  - The 3D structure of the brain may be a success factor
    - Benefits of energy savings due multicore organization can be extended in 3D
    - More communication energy savings due to shorter interconnects
    - Less energy costs for fan out
    - Very efficient heat removal by 3D microchannel cooling

PIONEERS IN COLLABORATIVE RESEARCH®

Nanofabrication

Research in Nanodevices will have a value if and only if

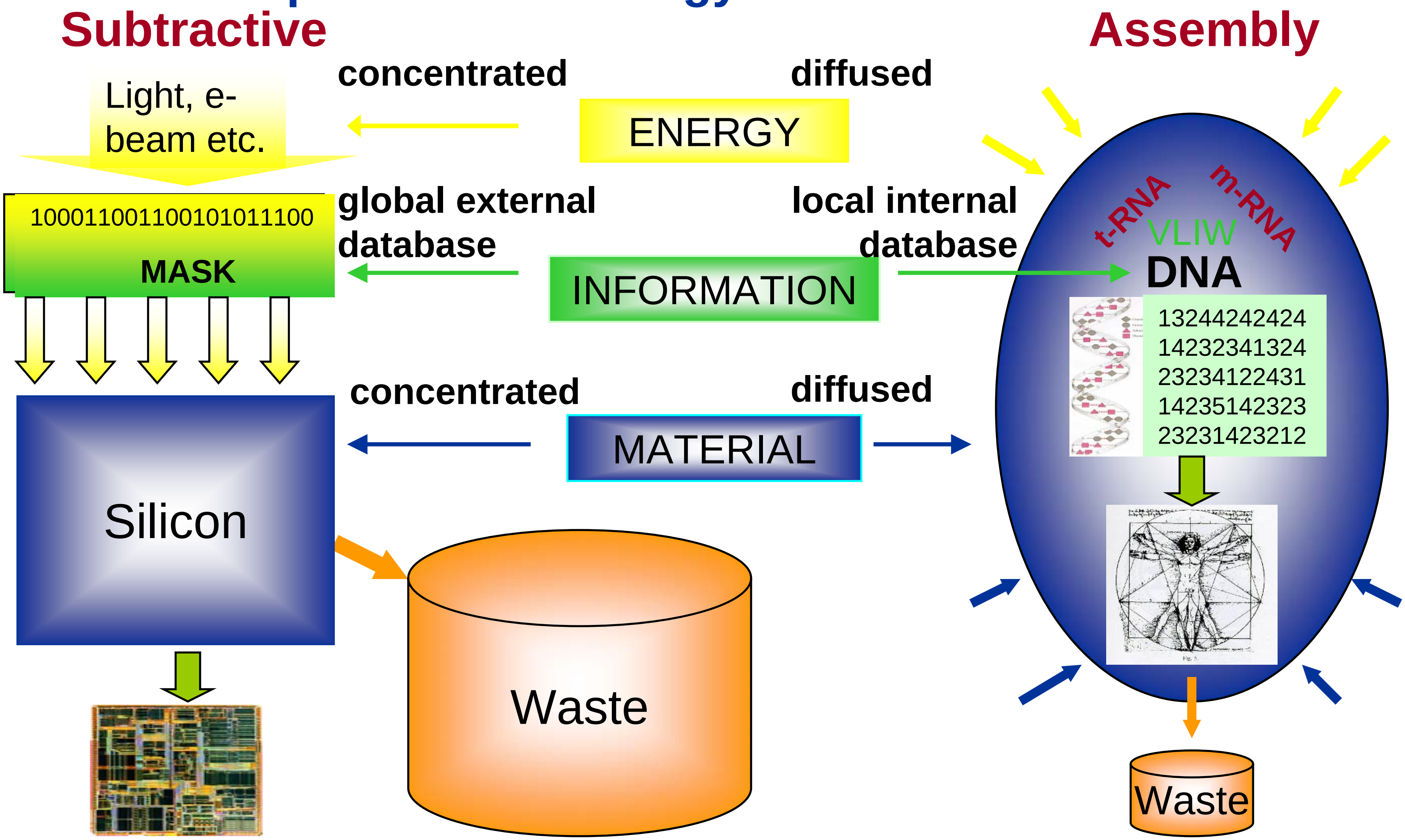
we can find a way to cost-effectively make working circuits by connecting together TRILLIONS of such devices



Can we 'teach' matter to organize into structures that we desire?

Manufacturing is Information Transfer
- Foundational knowledge base is needed

Complex Matter=Energy+Information+Material



Energetics of Assembly: Biological Inspiration

The 9-month development of a newborn:

Conventional Subtractive Manufacturing:
Energy per atom

$$\varepsilon_{total} = 2\times10^{-15}\,\frac{J}{at}$$

Input:

- Weight of newborn m=**3 kg**
- Composition: 70% H_2O + 30% $C_3H_6O_2N$ (amino acids)
- Additional calories for pregnant woman: **300 cal/day**
- Time: 9 month

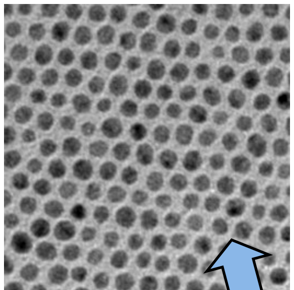
Calculation:

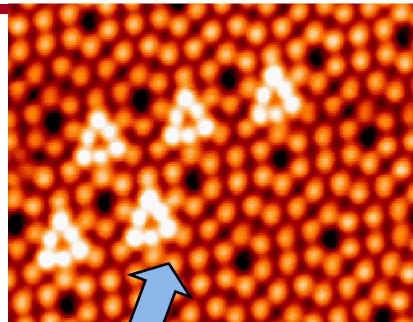
- Total additional energy of pregnancy: *E= 300cal/day*4.18J/cal*9mon*30day/mon=338580 J*
- Number of assembled molecules: $N = \frac{N_A}{M}m = 4.62x10^{25}$
- Energy per assembled molecule: $\varepsilon = \frac{E}{N} = 7.34x10^{-21}\,\frac{J}{molecule}$
- Assembly rate: **N/t=2x10^{18} molecule/s**

Assembly with less energy would ease manufacturing constraints

Assume a transistor occupies a volume of ~ 1x10^{6} nm^{3}, corresponding to ~50M silicon atoms. At biological growth rates, a 1Gb chip could be built in about 5 s.

Can we encourage matter to assemble into a structure we want?

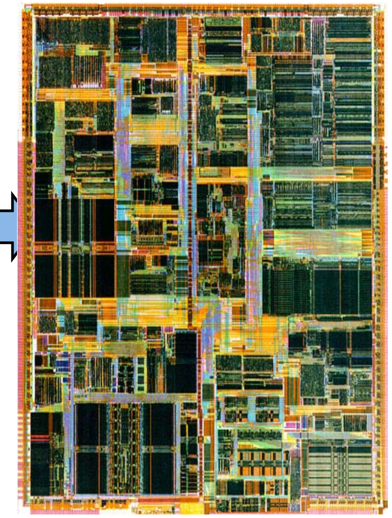




‘Self-assembly’ today: Regular arrays of simple elements…

…But

We need very complex structure with very high information content – *We need to tell atoms where to go*



<u>The key task is to find the information sources and channels to convey the assembly instructions.</u> For example, can we learn secrets of living matter to build things?

“We have no theory, that gives us a metric for the information embodied in a physical structure…This missing metric (may) be the most fundamental gap in the theoretical underpinnings of information science”.

Frederick Brooks (IBM 360 Architect, currently UNC Chapel Hill), 2003

A Scenario for IC Technology Transformation